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Abstract

In this paper, the near field coupling between an external hand-held loop antenna and an implantable miniature (1×1 mm) printed square spiral chip antenna used in bio-MEMS sensors for contact-less powering and RF telemetry is investigated. The loop and the spiral are inductively coupled and effectively form a transformer. The numerical results include the quasi-stationary magnetic field pattern of the implanted antenna, near zone wave impedance as a function of the radial distance and the values of the lumped elements in the equivalent circuit model for the transformer.

Introduction

In human space exploration programs there are several situations such as extravehicular activity, launch and de-orbit, and exercise in microgravity that require noninvasive monitoring of the physiological parameters (ref. 1). The sensors used in monitoring these parameters have to be small, light weight, wearable and inductively powered. In addition, the data from these sensors have to be wirelessly transmitted and recorded. As an example, the progress to date by our group in the development of an implantable biosensor system

for monitoring pressure is presented in (refs. 2 and 3). In this paper, the near field coupling characteristics between the loop antenna in the external hand-held device and the square spiral antenna in the implanted sensor are presented. These characteristics include the quasi-stationary or the near zone magnetic fields of the implanted antenna and the wave impedance as a function of the outward radial distance. In addition, when the loop is placed in close proximity to the spiral, the two antennas are inductively coupled and effectively form a transformer. Therefore a lumped element equivalent circuit model for the transformer is also presented. Several researchers in the past (refs. 4 to 8) have demonstrated inductive powering and data communications in implantable biosensors. Tables I and II summarize the inductor geometries and their coupling characteristics, respectively. However, the unique aspects of our approach are as follows: first, in our scheme the spiral antenna and the pressure sensor are monolithically integrated on opposite sides of a single silicon wafer. Thus the antenna, the sensor, and the control electronics can be mass-produced using commercial CMOS foundry process. Second, the dimensions of our antenna (1×1 mm) are significantly smaller than those in table I which results in a very compact design for the sensor unit.

TABLE I.—INDUCTORS USED IN HAND-HELD DEVICES AND IMPLANTED SENSORS

| External reader (transmitter) | | | Implanted sensor (receiver) | | | Reference |
|----------------------------------|------------------|--------------------------|--------------------------------|------------------|--------------------------|--------------------------------|
| Shape | Diameter (mm) | Self ind., (μ H) | Shape | Diameter (mm) | Self ind., (μ H) | |
| Single turn loop | 50 | 0.15 | Single turn loop | 50 | 0.15 | Huang and Oberle (ref. 4) |
| Circular coil | 90 | 26 | Circular coil | 20 | 25 | Hamici et al. (ref. 5) |
| Circular coil | 10 | 55 | Circular coil | 4.7 | 65 | Akin et al. (ref. 6) |
| Morphognostic coil | 48 | 3.0 | Morphognostic coil | 48 | 3.0 | Donaldson and Perkins (ref. 7) |
| Unknown | Unknown | 14.2 | Printed square spiral | 4.5 | 21.6 | Neagu et al. (ref. 8) |

TABLE II.—MEASURED COUPLING CHARACTERISTICS OF THE INDUCTORS IN TABLE I

| Link dist., (mm) | Coupling coeff. | Mutual ind., (μ H) | Received power or induced voltage | Operating frequency, (MHz) |
|---------------------|--------------------|----------------------------|--------------------------------------|-------------------------------|
| 90 | Unknown | Unknown | 2 mW | 27 |
| 20 to 40 | 0.014 to 0.027 | Unknown | 80 V | 2 |
| 5 | 0.082 | 4.9 | 20 V peak | 1 |
| 15 to 35 | 0.009 to 0.07 | Unknown | 20 V | 7.8 |
| 1 | 0.036 | 0.6 | 2.2 mW | 3 |

Near Field Characteristics of Implantable Square Spiral Chip Antenna

The inductive powering and telemetry principle in a biosensor system is schematically illustrated in figure 1. For the purpose of analysis, the implantable spiral chip antenna is approximated by a single turn wire loop of radius a , with constant current distribution I_0 , and circumference less than one-tenth of a wavelength as shown in figure 2. The magnetic and electric field components for a small circular loop in the near field region ($kr \ll 1$), where r is the radial outward distance, are expressed as (ref. 9)

$$H_r = A \cos \theta,$$

$$H_\theta = \frac{A}{2} \sin \theta$$

$$H_\phi = 0$$

$$E_\phi = -j\eta \frac{Akr}{2} \sin \theta$$

$$E_\theta = E_r = 0$$

Where $A = a^2 I_0 e^{-jkr} / 2r^3$, $k = 2\pi/\lambda$, λ is the free space wavelength and $\eta = 120\pi$.

The computed magnitude of H_r , H_θ and $H_{\text{sum}} = (H_r + H_\theta)$ as a function of the angle θ in the near field region is presented in figure 3. From this figure it is evident that in the near field region, the total magnetic field intensity is fairly uniform in all directions. Furthermore, the computed wave impedance Z_w , is expressed as

$$Z_w = (-E_\phi)/H_\theta = j\eta kr$$

In figure 4 computed Z_w is presented a function of the normalized radial outward distance r . This figure shows that in the near field region Z_w linearly increases from a few ohms to few hundred ohms as long as $kr < 1$. In addition, Z_w is independent of the loop radius a , and wire radius b . In view of the above, the implanted antenna and the antenna in the hand held device are inductively coupled in the near field region and effectively form a transformer. $Z_w = 377 \Omega$ when $kr = 1$ or $r/\lambda = 1/2\pi$ and Z_w remains constant at 377Ω for $kr > 1$ or in the far field region.

Lumped Element Equivalent Circuit Model for the Transformer

The lumped element equivalent circuit model for the transformer is shown in figure 5. In this figure, the primary

and secondary sides of the transformer represent the loop antenna in the hand held device and the miniature spiral implantable antenna, respectively. The circuit elements L_P and L_S are the self-inductances and R_P and R_S are the loss resistances of the two antennas, respectively. The mutual inductance is denoted as M and is expressed as

$$M = k_c \sqrt{L_P L_S},$$

where k_c is the coupling coefficient. The capacitance C_P is part of the input impedance matching circuit. The capacitance C_S represents the parasitic capacitance of the spiral and the tuning capacitance such as, the capacitance of the pressure sensor. As an example, for the spiral and the loop reported in prior publications by the authors (refs. 2 and 3), the computed circuit element values using expressions in (refs. 9 to 11) are presented in figure 5. The mutual coupling M is determined as explained in (ref. 10).

Conclusions

The near field coupling between an external hand-held loop antenna and an implantable printed square spiral chip antenna for bio-MEMS sensors applications is analytically investigated. The computed results show that the total magnetic field in the vicinity of the implanted antenna is fairly uniform in all directions and the wave impedance increases linearly with distance. Hence in the near field region, the spiral and the loop are inductively coupled and effectively form a transformer for which a lumped element equivalent circuit model and element values are presented.

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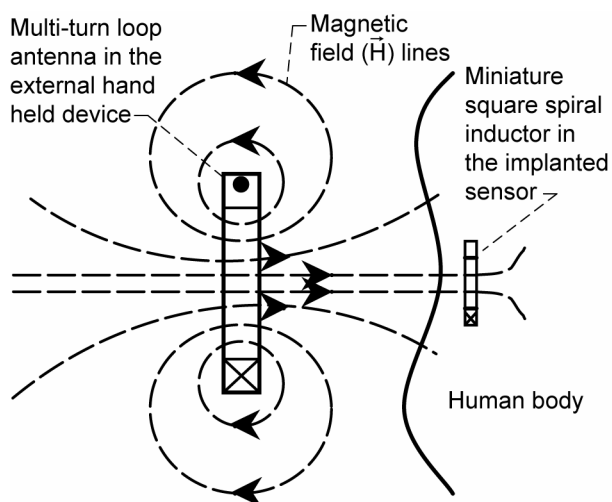


Figure 1.—Schematic representation of the inductively coupled powering and telemetry principle for implantable bio-MEMS sensors.

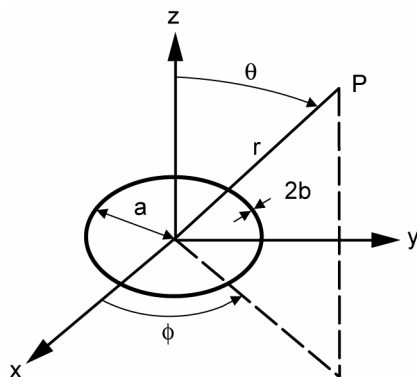


Figure 2.—Small circular wire loop with uniform current distribution. The wire radius is b .

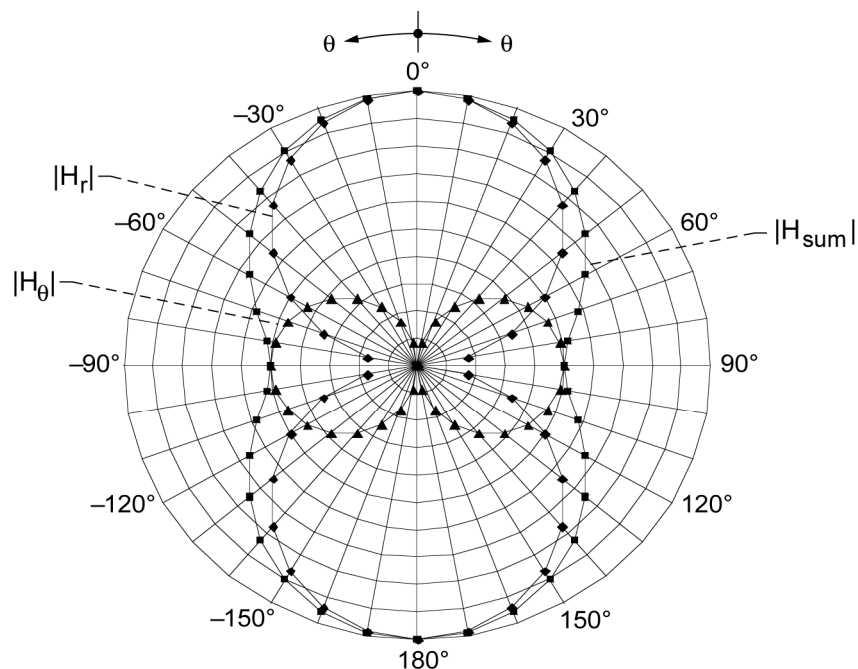


Figure 3.—Computed elevation plane amplitude of quasi-stationary (near field) magnetic field components H_r (♦♦♦), H_θ (▲▲▲), and H_{sum} (■ ■ ■) = ($H_r + H_\theta$) as a function of the angle θ for a small loop located in the x-y Plane. $a = 1$ mm, frequency = 403 MHz, $r = 10$ cm, and $I_0 = 1$ mA. The magnitude scale is 0.1/division.

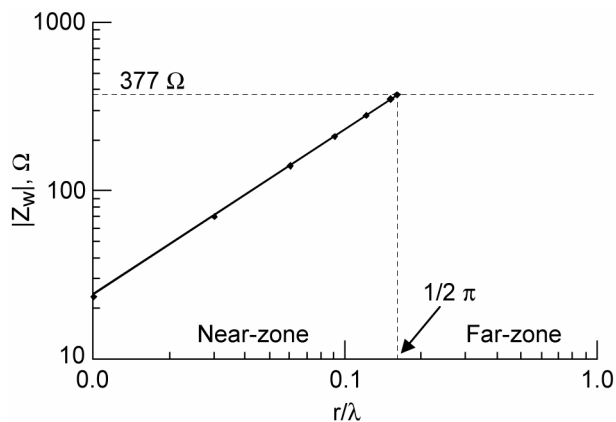


Figure 4.—Computed near field wave impedance of the idealized loop antenna versus normalized outward radial distance at 403 MHz.

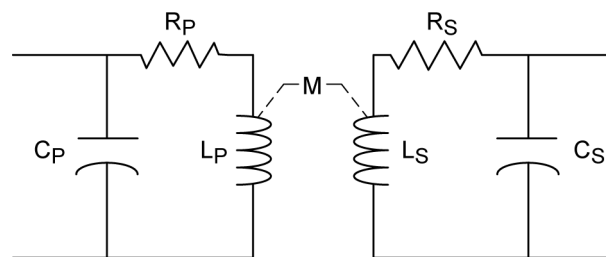


Figure 5.—The inductively coupled loop and spiral are modeled as an equivalent transformer circuit, $L_S = 117.6$ nH, $C_S = 100$ fF, $R_S = 56$ Ω , $R_P = 3.45$ Ω , $L_P = 0.43$ μ H, $M = 6.5$ nH when the two antennas are 5 cm apart.

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